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"Passive Cooling Systems in Iranian Architecture"

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Passive Cooling Systems in Iranian Architecture

They have no energy sources other than the sun and wind, and yet they circulate cool air through buildings and traditionally provided cold water and ice for the hot summer of the country's arid regions

by Mehdi N. Bahadori

The internal environment of a modern building can be a comfortable one no matter how uncomfortable the external environment is. In general the reason is that energy is freely spent to heat or cool the building. In earlier times, however, when energy was not so readily available and machines such as air conditioners did not exist, the designers of buildings had to rely on other stratagems to maximize the comfort of the internal environment. For example, the traditional architecture of many cultures in climates where the temperatures are uncomfortably hot during the day and uncomfortably cool at night features buildings with thick walls of brick or stone. Such walls are both insulators and reservoirs of heat, so that during the hotter hours of the day the flow of heat from the external environment to the internal one is retarded and during the cooler hours part of the heat stored in the walls warms the internal environment and the rest is lost to the external one. The net result is a flattening of the temperature-variation curve inside the building. In a period when the energy costs of buildings are being intensively reevaluated such stratagems clearly merit close consideration.

In Iran certain traditional building designs achieve more than a flattening of the temperature curve; they circulate cool air through the building and can even keep water cold and ice frozen from the winter until the height of the long, hot summer of the country's arid central and eastern plains. They do so without any input of energy other than that of the natural environment: hence they can be characterized as passive cooling systems. Some of these systems, for example curved-roof systems, were incorporated in buildings as early as 3000 B.C.; others, for example wind-tower systems, the cistern and the ice maker, may not have appeared until about 900 A.D. Many of the passive cooling systems are still in use at present.

The passive cooling systems take many forms. For example, in the arid regions of Iran buildings are traditionally constructed in clusters, attached to one another by common walls. Summer days in that climate are obviously characterized by large inputs of solar radiation. Clustering the buildings reduces their total exposed surface area, thereby reducing the solar-heat gain. (Clustered buildings were also easier to defend.) Heat transfer from the outside air is further reduced by limiting the number of doors and windows. The Iranian summer is windy and dusty, so that this feature also serves to reduce the amount of dust entering the buildings.

Although the summer days in the arid regions are extremely hot, the summer nights are cool. Several features of traditional Iranian architecture are designed to take advantage of this wide daily temperature range. The walls of the buildings are constructed of adobe brick, and like the walls in lands with a similar climate they are particularly thick, so that they have a high heat capacity. Therefore they can absorb the daily solar heat load rather than immediately transmitting it to the interior of the building. The heat is stored in the walls and later released to the interior of the building and to the cool night air.

Another way Iranian architecture has exploited the cool night air is courtyards planted with trees and shrubs. The plantings shield the walls of the rooms that open onto the courtyard so that the solar heat load on the walls is reduced. Both the walls and the plantings remain cool for several hours in the morning.

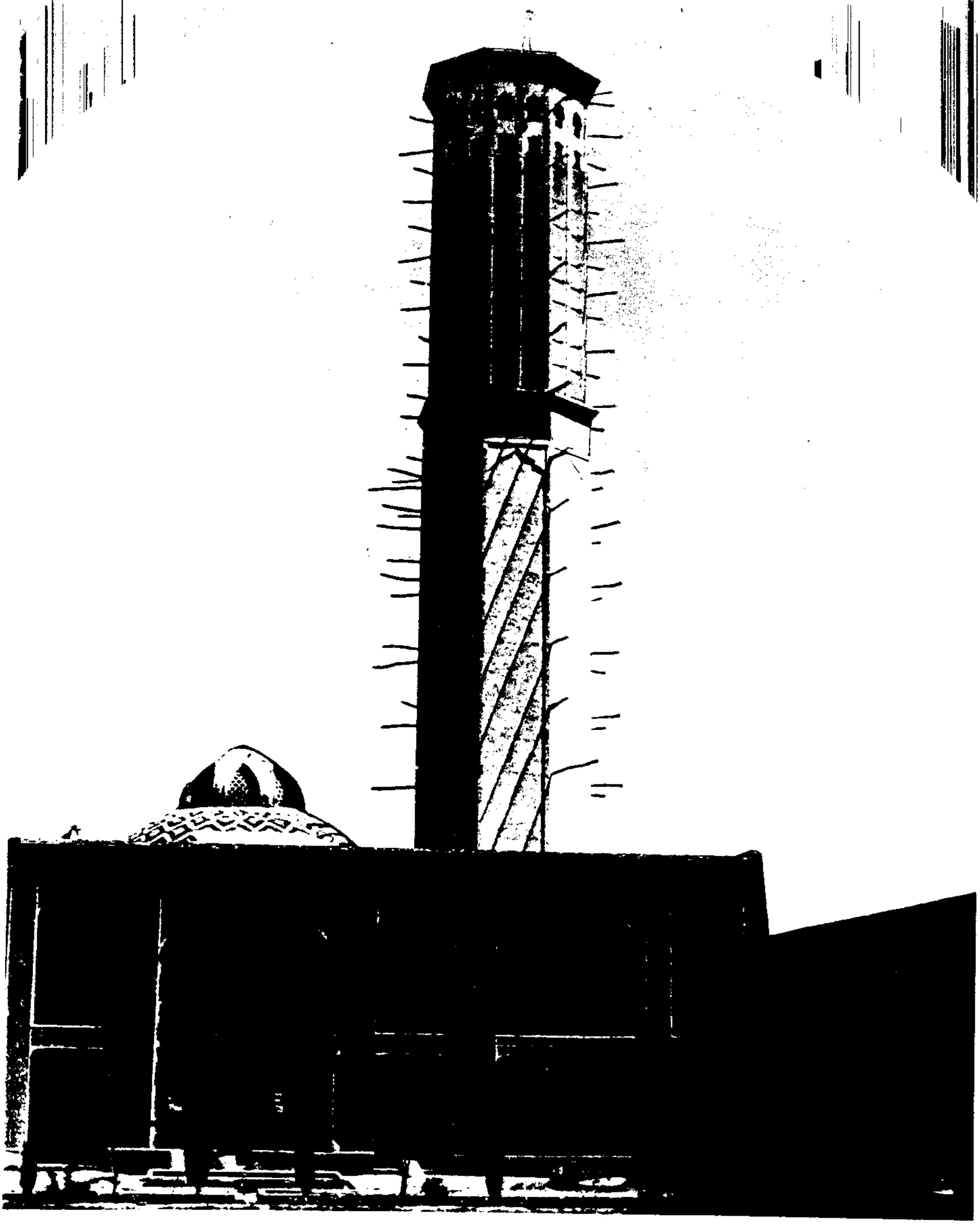
In earlier times the people who lived in the buildings of the arid regions of Iran also had behavioral ways of maximizing their comfort. For example, many people lived in basements, particularly during the hot summer afternoons, because the relatively low ground temperature kept the basement rooms cool. During the cool summer nights many people slept on the roof; the roofs had high parapets to ensure privacy, and the parapets also shielded the roofs from the dusty summer winds. Moreover, the streets were narrow, so that the parapets shaded the neighboring buildings (and pedestrians), reducing the solar heat load.

These approaches provided much relief from the severe climate, but four ingenious passive cooling systems achieve even more. They are the wind tower, the air vent, the cistern and the ice maker. I shall briefly describe each of the systems in turn.

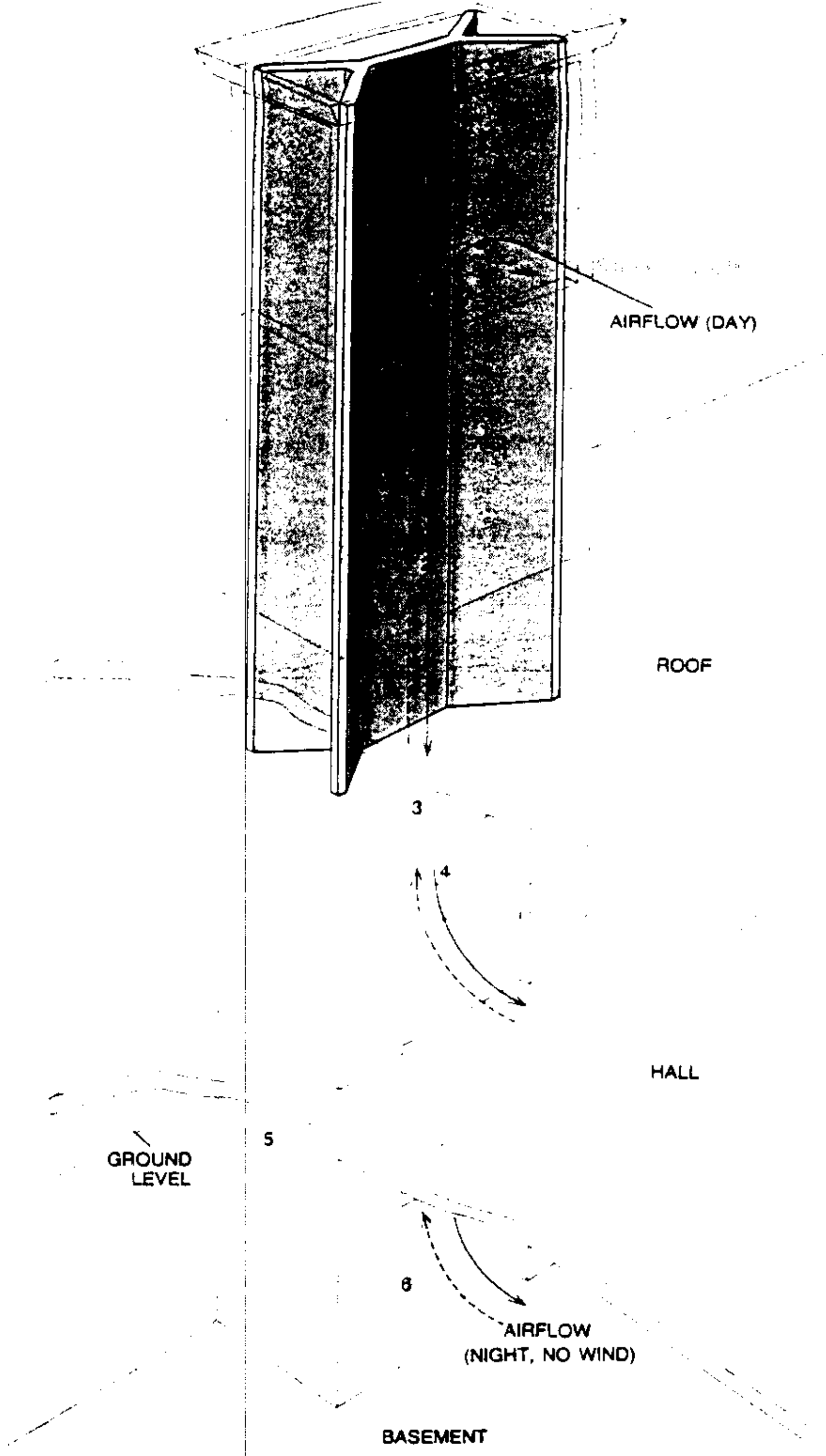
The arid regions of Iran have fairly fixed seasonal and daily patterns of wind. The "wind catcher," or wind tower, harnesses the prevailing summer winds to cool the air and circulate it through a building. A typical wind tower resembles a chimney, with one end in the basement of the building and the other end rising from the roof. The upper part of the tower is divided into several vertical air passages that terminate in openings in the sides of the tower. Tower designs differ in the height of the tower, the cross section of the air passages, the placement and number of the openings and the placement of the tower with respect to the structure it cools.

The wind tower operates by changing the temperature and thus the density of the air in and around the tower. The difference in density creates a draft, pulling air either up or down through the tower. Doors in the lower part of the tower open into the basement and the central hall of the main floor of the building. The flow of air through different parts of the building can be controlled by opening or closing the doors from the tower and the doors of the rooms off the central hall.

The operation of the tower depends



THREE PASSIVE SYSTEMS cool this building in the Iranian city of Yazd: a wind tower, a domed roof and an air vent. The wind tower acts to cool the ambient air and circulate it through the building. (Projecting from the tower are the ends of wood beams that reinforce it; the ends are left in place to provide support for scaffolds for maintenance of the exterior of the tower.) The domed roof to the left of the tower acts to keep the room under the roof cool. The small structure on top of the domed roof covers the air vent, which also acts to cool the room below and maintain a circulation of air through it. The three systems keep the building comfortable during the summer months.



A WIND TOWER OPERATES in various ways according to the time of day and the presence or absence of wind. The walls and airflow passages of the tower (*2*) absorb heat during the day and release it to the cool air at night. The next day the walls are cool. When there is no wind, hot ambient air (*solid arrows*) enters the tower through the openings in the sides (*1*) and is cooled when it comes in contact with the tower. Since the cooler air is denser than the warmer air, it sinks down through the tower, creating a downdraft (*2, 3, 5*). When there is a wind, the air is cooled more effectively and flows faster. Doors in the lower part of the tower (*4, 6*) open into the central hall and basement of the building. When these doors are open, the cooled air from the tower is pushed through the building and out the windows and other doors, entraining room air with it. The cooled air's path of circulation depends on the arrangement of doors in the tower and the building. (Some of the air flowing down the windward passages of the tower is forced back up through the opposite air passages and out through the leeward openings.) When there is no wind at night (*broken arrows*), the tower operates like a chimney. Heat that has been stored in walls during the day warms the cool night air in the tower. Since the warmer air is less dense than the cooler air, the pressure at the top of the tower is reduced, creating an updraft. Air in building is entrained up through the tower and cool night air is pulled into building through the doors and windows. When there is wind at night, air flows down tower and through building. Since tower walls warm night air before it enters building, rate of cooling can be lower.

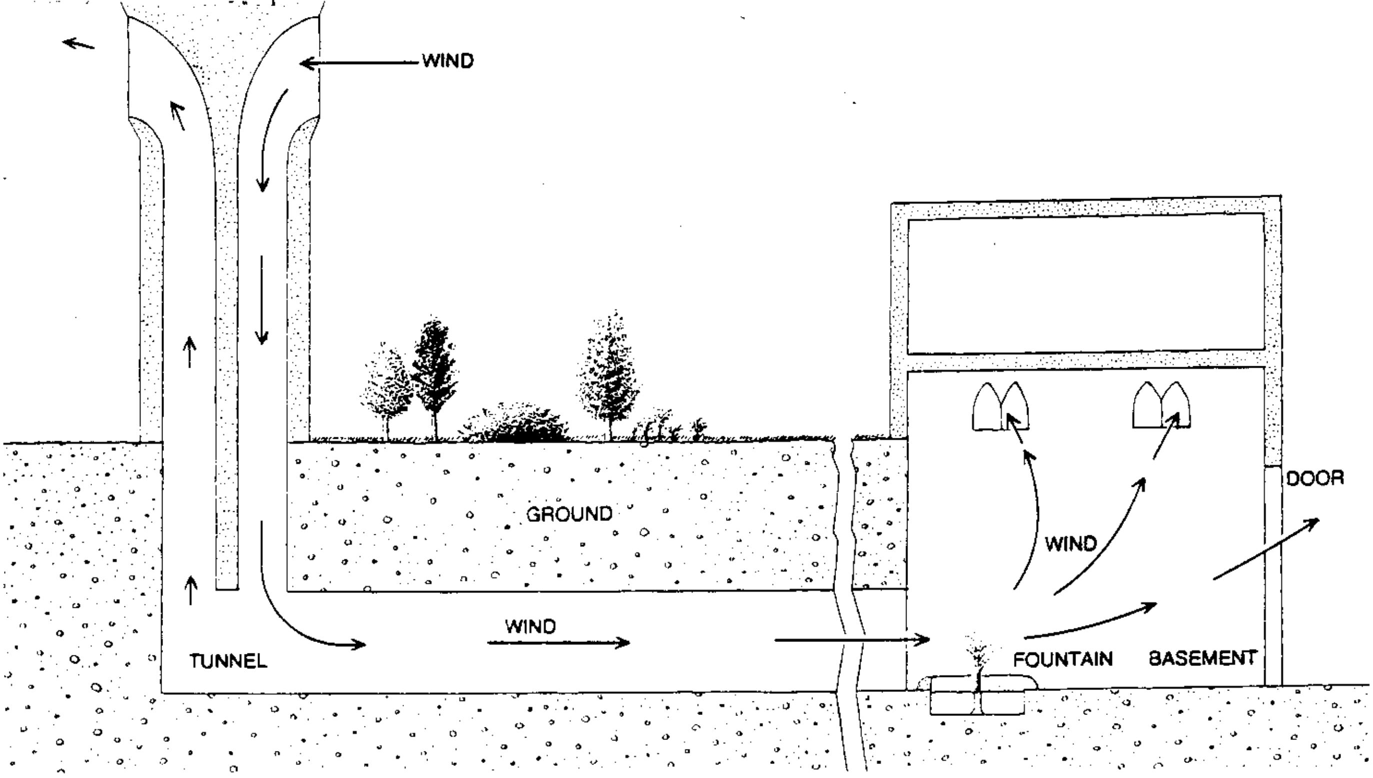
When there is no wind at night, the tower operates like a chimney, circulating air by pulling it upward and out through the tower openings. It works as follows. The tower walls (including the internal walls that separate the air passages) have absorbed heat during the day. Since heat flows in the direction of decreasing temperature, the walls transfer heat to the cool night air in and around the tower. The configuration of the upper part of the tower, namely the thickness of the walls and the cross section of the air passages, is designed to provide sufficient heat-storage capacity and heat-transfer area for the task. Since the warmer air is less dense, the air pressure at the top of the tower is reduced, creating an upward draft. The air in the building is drawn up through the tower, and cool ambient air is pulled into the building through the doors and windows. The process continues during the night, so that cool air is kept circulating through the building.

When there is a wind at night, the air is forced to circulate in the opposite direction: the rooms are cooled by night air coming down the tower rather than through the doors and windows. Here, although the night air is warmed by the tower walls before it enters the building, the cooling can still be sufficiently effective to bring the temperature in the building close to that of the ambient air. The external walls and the roof of the building radiate stored solar heat to the night sky, which further cools the building. Since the desert sky tends to be very clear at night, the radiative heat transfer to it is extremely effective.

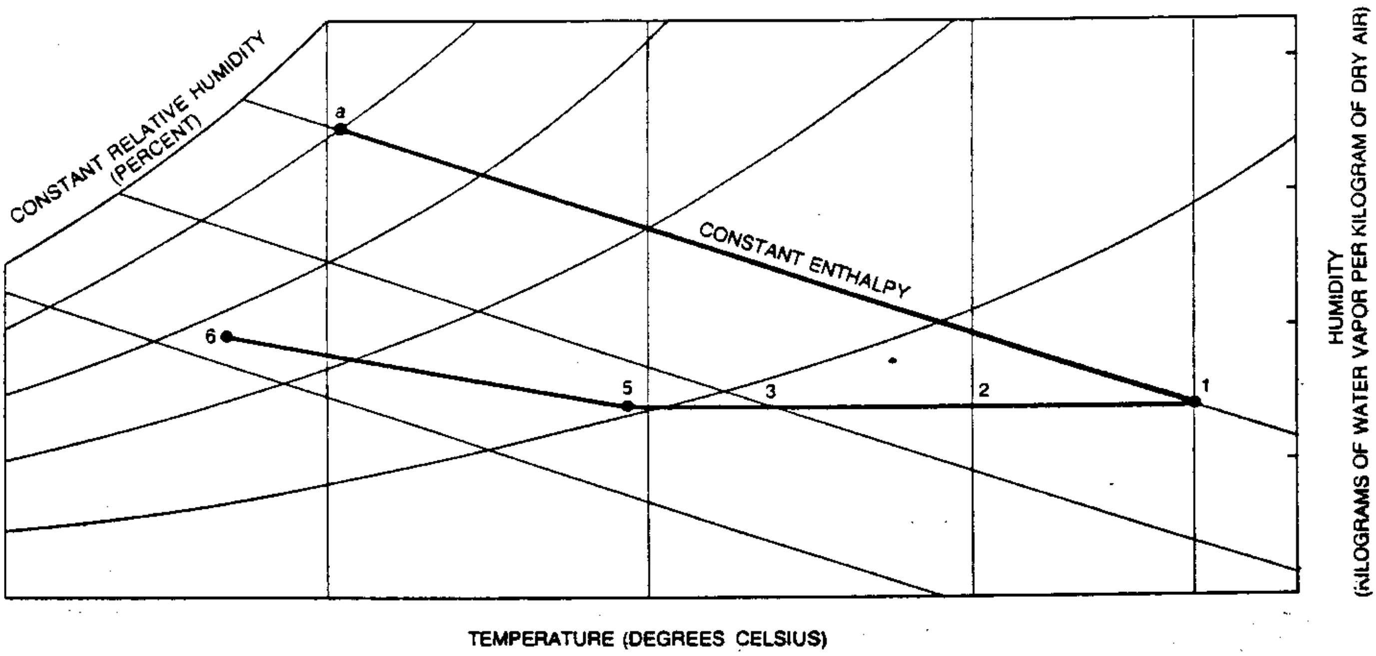
When there is no wind during the day, the operation of the tower is the reverse of a chimney. The walls of the upper part of the tower have been cooled during the previous night. Hot ambient air comes in contact with them and is cooled. Being denser than the hot air, the cooled air sinks down through the tower, creating a downdraft. The cooled air is pushed through the building and eventually out through the doors and windows, entraining room air with it.

When there is a wind during the day, the rate of circulation is increased. The cool air can be circulated through any room in the building by the appropriate arrangement of doors in the tower and the rooms. If there is no wind during the day, when the temperature of the tower reaches that of the ambient air, the circulation of air down through the tower and into the building ceases and the tower begins to operate like a chimney. (Of course, the operation of the tower is not constant throughout the day and night: the cooling effect and the duration of each phase of tower operation change according to fluctuations in the air temperature, the intensity of solar radiation, the wind velocity and so on.)

The openings in the upper part of



TWO KINDS OF COOLING operate in the passive system shown in this section. In sensible cooling heat loss from the air results in a decreased air temperature but no change in the water-vapor content of the air. Air in the upper part of a wind tower is sensibly cooled. When water is introduced into a system, evaporative cooling occurs. Such cooling involves a change in both the water-vapor content and the temperature of the air. When unsaturated air comes in contact with water, some of the water is evaporated. This process is driven by heat from the air, so that the temperature of the air is decreased as its water-vapor content is increased. A wind-tower system that cools air evaporatively as well as sensibly is particularly effective. In most wind towers water in the ground seeps through to the inside of the basement wall of the tower, so that air passing over the wall is evaporatively cooled. Evaporative cooling plays an even larger part in the system shown here. The wind tower is placed some 50 meters from the building and is connected to it by a tunnel. When the trees, shrubs and grass in the ground over the tunnel are watered, water seeps through the soil and keeps the inside surfaces of the tunnel walls damp. Thus air from the tower is evaporatively cooled as it passes through the tunnel. Pool and fountain in the basement of the building further cool the air.



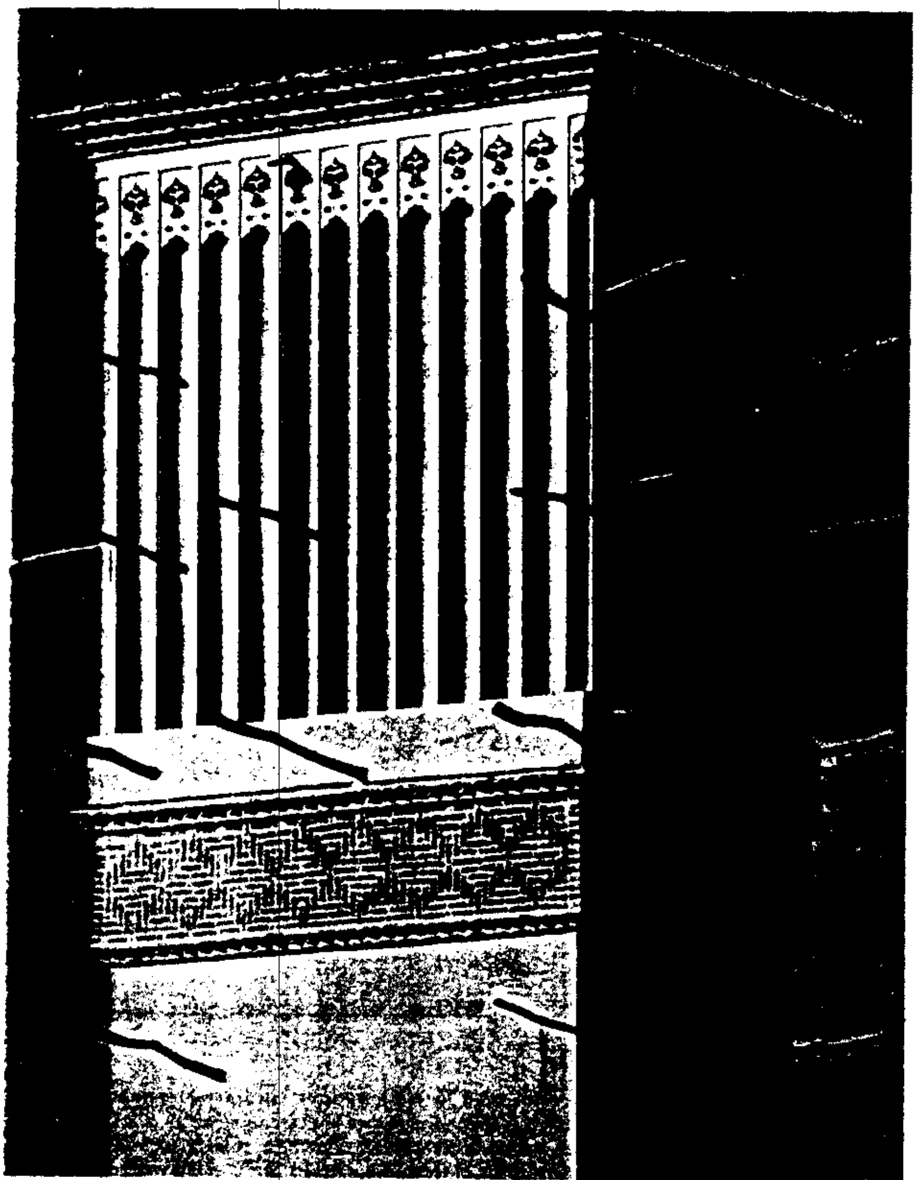
PSYCHROMETRIC CHART shows the conditioning of air during the daytime as it flows through the wind tower that appears in the illustration on the opposite page. Air flowing down the tower is sensibly cooled (*1, 2, 3, 5*), so that the temperature of the air decreases but the water-vapor content remains the same. Since cooler air can hold less water than warmer air, however, the relative humidity (the ratio of the actual vapor pressure to the maximum vapor pressure at the same temperature) increases. When air flows over the damp basement wall of the tower, it is also cooled evaporatively and water vapor is added to it (*5, 6*). Hence the temperature of the cooled air decreases further, and its water-vapor content and relative humidity increase before it enters the basement of the building. The line *1–a* shows the air conditioning that occurs when only evaporative cooling is operating. It is a line of constant enthalpy because no heat is entering or leaving the system of air and water vapor. The numbers that are shown on the chart are the same as those in the illustration on the opposite page.

the tower are placed in pairs so that for every windward opening there is a leeward one. When the doors in the lower part of the tower are closed, wind flowing down the tower is forced back up through the opposite air passages and out through the leeward openings. In fact, even when the tower doors are open, some of the air flowing down the tower leaves by those openings. The upward draft created in the opposite passages entrains room air and pulls it up the tower. In other words, in the normal operation of a wind tower there is always some entrainment of room air through the leeward openings. In this way the tower provides a continuous circulation of air through the building.

So far I have discussed only those temperature changes in wind towers that are due to what is known as sensible cooling. Sensible cooling occurs when there is a change in the temperature of air without a change in its humidity, or water-vapor content. Evaporative cooling occurs when there is a change in the temperature and the humidity, and it can play an important role in the operation of wind towers. For example, when the basement wall of a tower is damp, as is often the case, the air coming down the tower is cooled both sensibly and evaporatively. In other words, water on the wall absorbs enough heat to be vaporized. Since vaporization requires relatively large amounts of heat, wind towers that incorporate evaporative processes can cool the air quite effectively. In fact, before refrigerators came into wide use in Iran, the damp basements of wind towers served as cold-storage areas. Moreover, the humidifying of the air that accompanies evaporative processes is an important contribution to comfort at lower temperatures.

Another way of exploiting evaporative cooling is to place a small pool with a fountain at the bottom of the wind tower. Wind can be sensibly and evaporatively cooled coming down the tower and then evaporatively cooled by the pool and the fountain before it enters the rooms of the building. There are many buildings with towers of this type in the Iranian city of Yazd.

A wind tower in the city of Bam is employed in a different way. The tower is placed about 50 meters from the building it serves, and an underground tunnel runs from the bottom of the tower to the basement of the building. The ground over the tunnel is planted with trees, shrubs and grass. When the ground is watered, the water diffuses through the soil so that the tunnel walls are kept damp, and air coming down the tower and through the tunnel is sensibly and evaporatively cooled. A pool and fountain where the cooled air enters the basement furnish further cooling.

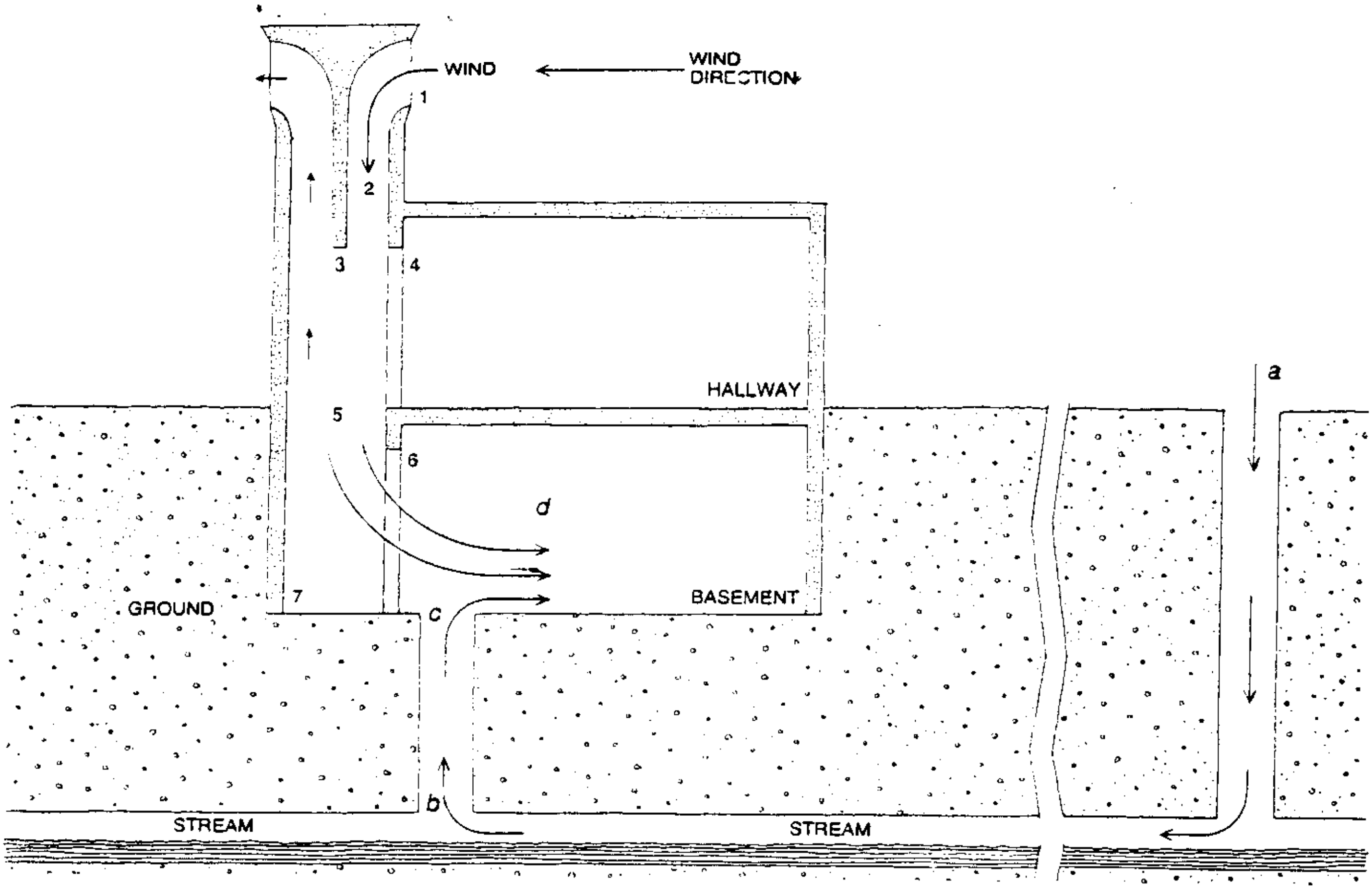


CLOSEUP VIEW OF THE TOP OF A WIND TOWER in Yazd shows the ends of its reinforcing beams. The tower is about 13 meters high and its openings are about three meters high. The tower in illustration on page 145 is about 34 meters high; its openings are about 11 meters high.

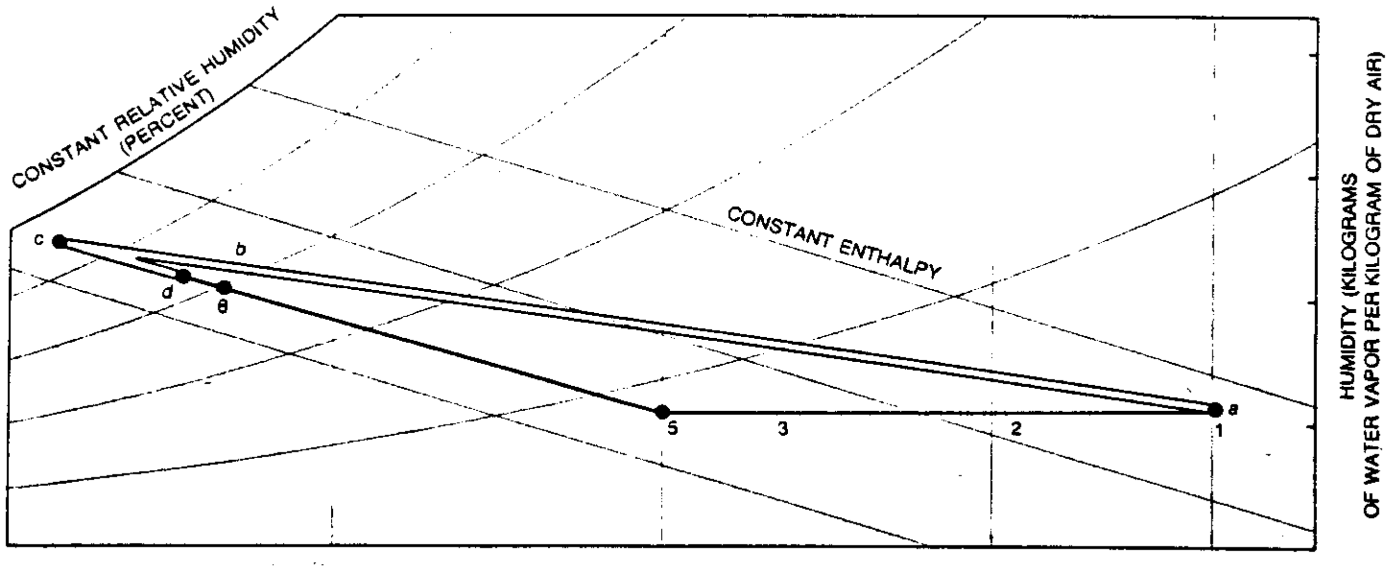
Another variation of the wind tower operates in conjunction with an underground stream. A vertical shaft runs from the stream to the basement of the building, and the tower is placed so that wind coming through the basement door of the tower goes over the top of the shaft. When air flowing through a large passage enters a smaller one, its velocity increases and its pressure decreases. The cross-sectional area of the tower is larger than that of the door, and so the pressure of the air from the tower is still decreased as it passes over the top of the shaft. When air from the tower flows at a high velocity across the top of the shaft, a point of entrainment is created there. The result is that air from the shaft is drawn into the flow of tower air.

Air enters the passageway of the underground stream through other shafts that connect the passageway to the surface. Since underground water is usually cold, air passing over it is effectively cooled, and so the cooling rate of wind-tower systems operating in conjunction with underground streams is quite high. Here again the air at the point of entrainment is so cool that food was often stored near the opening of the shaft. The cooling is effective even on windless nights, when the tower operates like a chimney: the outside air flows over the underground stream, where it is evaporatively and sensibly cooled, and then up through the shaft into the building. It mixes with the basement air and is finally vented from the top of the tower.

One problem with wind towers is that they admit dust, insects and birds to a building. Newer towers are equipped with screens to keep out at least the insects and birds. Taller towers bring in less dust, but they are expensive to build and maintain. Another way of keeping the dust out of a building is to construct a tower with a base that is wider than the rest of the tower. Increasing the cross-



UNDERGROUND STREAM and a wind tower are an effective cooling combination. In the system shown here a shaft connects the stream to the surface and another shaft connects the stream to the basement of the building to be cooled. Hot, dry ambient air enters the passageway of the stream through a shaft outside the building (*a*) and is both sensibly and evaporatively cooled as it flows along the water (*b*). Since underground water is usually cold, the rate of cooling is quite high. The wind tower is placed so that wind flowing through the basement door of the tower passes over the top of the shaft from the stream. When the air flows from a large passage (the tunnel) through a smaller one (the door), its pressure decreases. The pressure of the air from the tower is still diminished when it passes over the top of the shaft, so that cold, moist air from the shaft is entrained by the flow of cooled air from the tower (*c*). The mixture of air from the shaft and air from the tower (*d*) circulates through the basement. Single underground stream can serve several wind-tower systems of this type.



CONDITIONING OF AIR by a wind-tower system with an underground stream is shown in this psychrometric chart. Warm, dry outside air enters the system at two different points (*1, a*). The air entering the wind tower (*black line*) is sensibly cooled as it flows down the tower; the temperature of the air decreases and its relative humidity increases (*1, 2, 3, 5*). The air is also evaporatively cooled as it flows over the damp basement wall of the tower; the temperature decreases, and both the water-vapor content and the relative humidity increase (*5, 6*). The warm, dry air that enters the passageway of the underground stream (*double line*) is sensibly and evaporatively cooled as it flows over the cold water. Thus there is a large drop in the temperature of the air and a large increase in its water-vapor content and relative humidity before it flows up through the shaft to the basement of the building (*a, b, c*). In the basement the cold, moist air from the passageway of the underground stream (*c*) mixes with the warmer, drier air from the wind tower (*6*). The final mixture (*d*) is the air that circulates through the basement. The numbers and letters that are shown on the chart are the same as those in the illustration above.

sectional area of the airflow reduces the wind velocity at the bottom of the tower, which allows the dust to settle on shelves called dust pockets. The placement of the openings at the top of the tower can also control the infiltration of dust: in areas where dusty winds blow in one direction and dust-free winds blow in the other the openings are placed accordingly. Similarly, in areas where there are prevailing winds the openings are placed to take advantage of them.

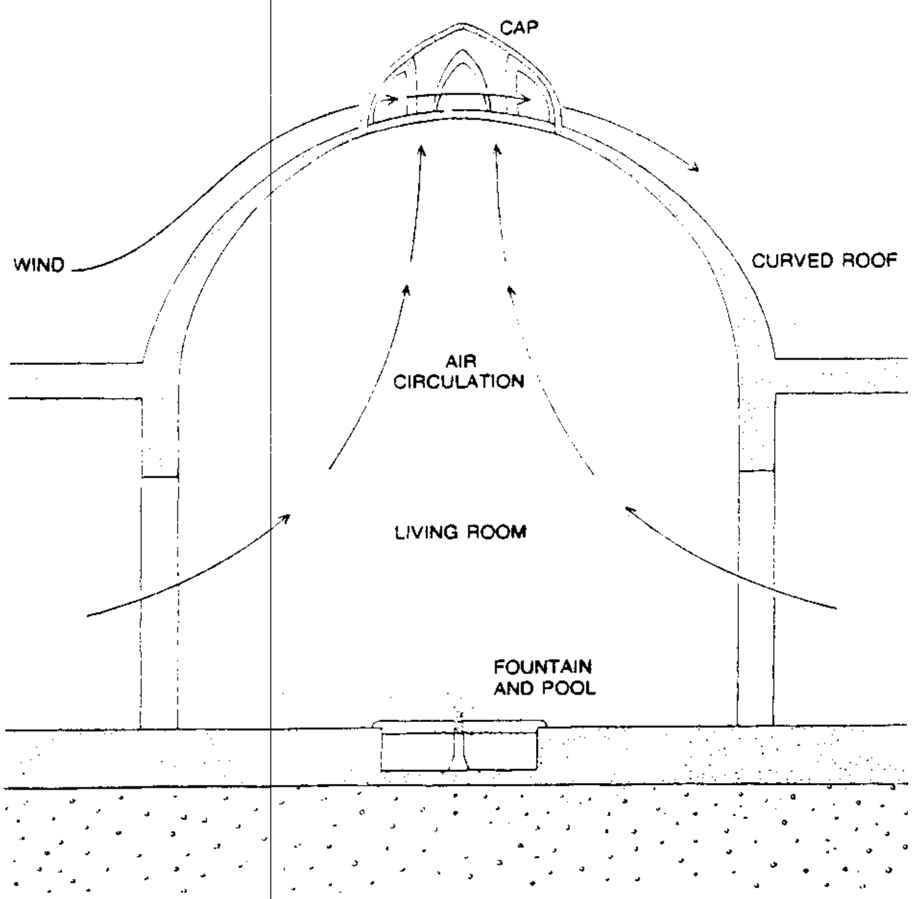
Wind towers are still in service in Iran and are even included in some new buildings. They are of course intended only for summer use and must be properly closed in winter. For example, in Bam the towers are sealed off by thin walls. If the towers are not closed in winter, they greatly increase infiltration heat losses, that is, losses to the cold ambient air that has leaked into the building.

Wind towers can be employed in conjunction with curved roofs, which are another source of comfort in Iran's hot summer climate. Curved (domed or cylindrical) roofs offer many advantages over flat ones. They are inherently stronger; therefore they can be made lighter and do not require the support of wood beams, which are scarce in the desert areas. Furthermore, the hot air that gathers under a curved roof is well above the living area of the room the roof covers. In this way the room is kept more comfortable, and heat transfer from the roof to the room is limited because a high temperature is maintained next to the roof.

Any roof absorbs solar heat directly by radiation, and flat and curved roofs of the same base area absorb about the same amount of solar radiation. A roof loses most of its heat, however, not by radiation but by convection: that is, the principal heat loss depends on the movement of air across the roof. A curved roof has a larger convection heat-transfer area and transfers heat more efficiently than a flat roof. Therefore a curved roof is more easily cooled.

A curved roof is most effective when it incorporates an air vent. The operation of an air vent depends on the fact that when air flows over a cylindrical or spherical object, the velocity at the apex of the object increases; consequently the pressure at the apex decreases. If there is a hole at the apex of a domed or cylindrical roof, the difference in pressure induces the hot air under the roof to flow out through the vent.

An air vent is usually protected by a small cap in which there are openings that direct the wind across the vent. Since the functioning of the vent depends on air flowing over a curved surface, roofs with vents are oriented to present the maximum curve to the wind. In areas where the wind is a prevailing one cylindrical roofs are built with the axis of the cylinder perpendicular to the wind direction; in areas where the winds blow in all directions domed roofs are employed. Air vents are usually placed over the living rooms of buildings.

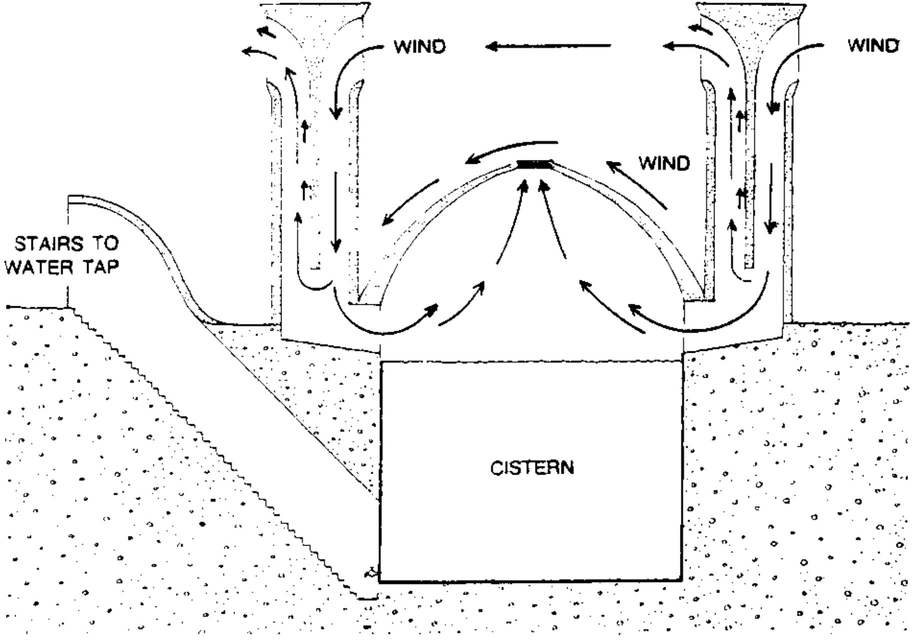


AIR VENTS are employed in areas where dusty winds make wind towers impractical. Such a vent is a hole cut in the apex of a domed or cylindrical roof. Openings in the protective cap over the vent direct wind across it. When air flows over a curved surface, its velocity increases and its pressure decreases at the apex of the surface. The decrease in pressure at the apex of a curved roof induces the hot air under the roof to flow out through the vent. In this way air is kept circulating through the room under the roof. Air vents are usually placed over living rooms, often with a pool of water directly under vent to cool air moving through the room.

A passive cooling system of the cistern type incorporates several other passive systems. The cistern is a reservoir 10 to 20 meters deep, sunk into the ground, covered by a domed roof and surrounded by several wind towers. In some areas on the arid plains of Iran water is brought from the highlands by the system of underground aqueducts called qanats. The purpose of the cisterns is to hold the water at a reasonably low temperature during the hot summer months. The design of the cistern takes advantage of the seasonal temperature changes in the desert and the insulating properties of the ground.

In the arid zones of Iran the winter nights are very cold. In winter cold water is admitted to the cisterns, partly filling them. In summer the domed roof of the cistern is warmed, and so is the air and the top layer of water in the cistern. Before the deeper layers of the water are warmed, however, the water in the top layer evaporates and the water vapor is carried away by a draft across the surface, maintained by the wind towers. In this way the water is kept cold.

A cistern cooling system operates in one of two ways. If it has a domed roof with an air vent in it, the air flows down the wind tower, across the water and up through the vent. This airflow entrains the mixture of air and water vapor under the roof. If the cistern has an air vent, however, dust, insects and other matter can fall into it and foul the water, and so some cisterns are constructed without vents. In these cisterns the flow of air from the tower is short-circuited: the air flows down through the passages on one side of the tower and back up through the passages on the other side, entraining the mixture of air and water vapor in the cistern and inducing it to flow out through the openings on the leeward side of the tower. Cisterns of either type are not much used at present because although the water they supply is cold, it is also stagnant and therefore



CISTERN is filled with cold water during winter nights, when the temperature in the arid regions of Iran is usually only a few degrees above freezing. The wind towers that surround the cistern keep the water cold for use during the hot summer months. When the domed roof of the cistern is heated by the sun, it warms the air over the water in the cistern and increases the rate at which it evaporates. The towers maintain a draft across the surface of the water, so that the water vapor is removed, saturation is prevented and evaporation can continue. The deeper layers of the water are little warmed because the heat from the air is almost entirely spent in evaporating the water at the surface. When there is an air vent in the roof of the cistern, wind flows down the towers, across the water and up through the vent (*black arrows*), entraining vapor-laden air from the cistern out through the vent. When there is no air vent, wind flows down the towers and is forced back up through the air passages on the leeward side of the towers (*colored arrows*). The updraft created in the leeward passages entrains cistern air out through the leeward tower openings. Cistern is partly buried to take advantage of the insulating properties of ground. Domed roof is more easily cooled than a flat one and transmits less heat into cistern.

not safe for direct human consumption.

A cistern system effectively operates by storing energy from one season to another. Many passive cooling and heating systems operate on this principle. Another example is the traditional ice-making system of Iran. (Like the cistern, the ice maker has been abandoned for health reasons.) In Iran's arid regions the nighttime temperature of the air in winter is usually only a few degrees above freezing. With an ice maker, ice can be produced in winter and stored for the summer. The system depends on ra-

DOMED ROOF AND WIND TOWERS of a cistern in Yazd appear here. Towers are about 12 meters high; cistern is about 12 meters deep and can hold some 1,000 cubic meters of water.

diation losses to the sky on clear, cold winter nights.

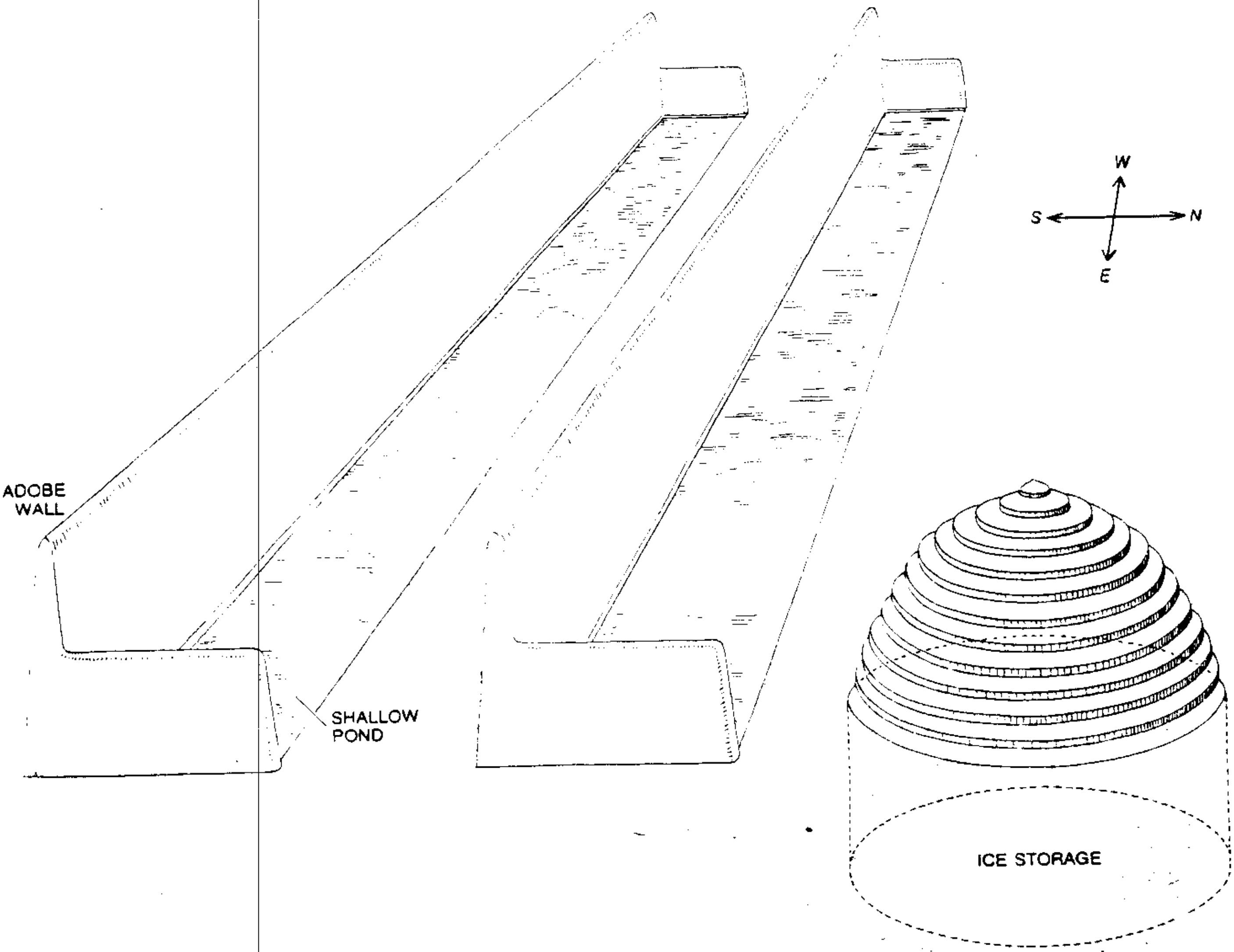
The ice maker consists of a large storage pit 10 to 15 meters deep and one or more shallow rectangular ponds, 10 to 20 meters wide on a north-south axis and several hundred meters long on an east-west axis. An adobe wall is built on the south side of each pond, high enough to shade the entire width of the pond during the ice-making season. Lower walls at the east and west ends of the pond shield it from early-morning and late-afternoon solar radiation.

On cloudless winter nights each pond is filled with water. Water in such a pond loses heat to the sky by radiation and receives heat from the air by convection and from the ground by conduction. The walls along the pond, however, shield the pond from the wind and thus reduce the heat gain by convection. (When there are several ponds, their parallel walls contribute to the overall shielding effect.) Under these circumstances the heat loss by radiation to the night sky is sufficient to freeze the water in the pond.

The weather conditions dictate to what depth the water can be made to freeze. Sometimes the pond is filled a few centimeters at a time during the night, which increases the rate of ice formation. On the following day the ice is cut up and placed in the storage pit. While that is being done the walls of the pond help to keep the ice from melting in the heat of the daytime sun. On the other hand, conduction from the ground tends to melt the bottom of the ice, so that it can be more easily removed.

A passive cooling system exploits the very features of the climate it seeks to overcome. For this reason the passive cooling and ventilating systems of Iran cannot be applied at random in other areas of the world. These systems could work well, however, in climates similar to the climate of Iran. For example, although the cistern and ice-making systems have been abandoned for public-health reasons in Iran, they could be employed in Iran and elsewhere to supply cold water and ice for purposes other than direct human consumption.

In climates where the passive cooling systems of Iran cannot be applied they should still be of interest. They demonstrate the possibilities of working with rather than against the external environment. In the future architects and engineers will need to take more account of climate and might well examine the possibilities it affords for passive heating, cooling and ventilating systems. With this information they should be able to design buildings that have modern amenities and yet consume minimal amounts of energy.



ICE MAKER is a passive cooling system that takes advantage of the near-freezing temperatures of winter nights in the desert. Several shallow ponds, 10 to 20 meters wide on a north-south axis and several hundred meters long, are filled with cold water on winter nights. A tall adobe wall on the south side of each pond and lower walls at the east and west ends shield the pond from the wind. At night the water in the pond loses heat to the sky by radiation and gains heat from the ground by conduction and from the air by convection (that is, by the movement of air across the water surface). Shielding the pond from the wind reduces the heat gain by convection, so that on cloudless nights the heat loss to the sky by radiation is sufficient to freeze the water. On the following day the ice is cut up and placed in a covered storage pit 10 to 15 meters deep. The walls shade the pond during the day so that the ice does not melt before it can be cut up and stored.